Sea level at Saint Paul Island, southern Indian Ocean, from 1874 to the present

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[1] A data archeology exercise was carried out on sea level observations recorded during the transit of Venus across the Sun observed in 1874 from Saint Paul Island (38°41′S, 77°31 E) in the southern Indian Ocean. Historical (1874) and recent (1994–2009) sea level observations were assembled into a consistent time series. A thorough check of the data and its precise geodetic connection to the same datum was only possible thanks to the recent installation of new technologies (GPS buoy and radar water level sensor) and leveling campaigns. The estimated rate of relative sea level change, spanning the last 135 years at Saint Paul Island, was not significantly different from zero (-0.1 ± 0.3 mm yr^{-1}), a value which could be reconciled with estimates of global average sea level rise for the 20th century assuming the DORIS vertical velocity estimate at Amsterdam Island (100 km distant) could be applied to correct for the land motion at the tide gauge. Considering the scarcity of long-term sea level data in the Southern Hemisphere, the exercise provides an invaluable additional observational constraint for further investigations of the spatial variability of sea level change, once vertical land rates can be determined.

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1. Introduction

[2] The study of global long-term sea level variability is a subject of major importance nowadays, due to its association with climate change and its direct societal impact. Enormous efforts have been undertaken to better understand the mechanisms that drive such variability, and previous works highlight the complexity of the response both over temporal and geographical scales [*Holgate and Woodworth*, 2004; *Jevrejeva et al.*, 2006]. Even if satellite altimetry has proven to be a very powerful technology to derive a global overview of variability, such a picture can only be provided for the last two decades at most. Thus, one of the issues typically raised is the scarcity of sea level time series which span the past century and longer [e.g., *Douglas*, 2001; *Woodworth*, 2006]. On the other hand, the availability of such time series is mostly restricted to continental coastlines, and information about open ocean processes is limited, especially for the Southern Hemisphere. All these considerations make Saint Paul Island, due to its remote location in the southern Indian Ocean, a site of particular interest for sea level studies.

[3] Saint Paul Island (Figure 1) is an ancient volcanic island located in the southern Indian Ocean (38°41′S, 77°31′E), part of the Terres Australes et Antarctiques Françaises (TAAF). It was discovered in the sixteenth century and annexed by France in 1843. The volcano collapse, some thousand years ago, brought about the inundation of its crater. Together with Amsterdam Island (approximately 100 km north of Saint Paul Island), it represents one of the few emergent points of a vast submarine volcanic plateau, situated along the Southeast Indian Ridge [*Doucet et al.*, 2003]. Saint Paul and Amsterdam islands have a mild oceanic climate strongly influenced by the subtropical anticyclone and the westerlies, known as the roaring forties [*Miller et al.*, 1993]. The presence of the Kerguelen plateau south of Saint Paul Island causes a significant component of the Antarctic Circumpolar Current (ACC) to be deflected to its northernmost position and to pass between Kerguelen and Saint Paul/Amsterdam islands [*Park et al.*, 2009].

[4] As early as in 1874, Saint Paul Island was already the destination of a scientific expedition. Sea level measurements taken at that time enabled the calculation of a mean sea level (MSL) which was engraved on a rock (Figure 2). This mark has been recently discovered and leveled with respect to the local hydrographic zero (hereafter called Zh, Figure 3) defined for Saint Paul Island.

[5] This paper will focus on the study of long-term sea level change based on a thorough analysis of the rescued 1874 data along with the most recent data obtained from a modern tide gauge installation. It will, therefore, represent one of the few data archeology exercises devoted to estimate the sea level change from historical information recorded in

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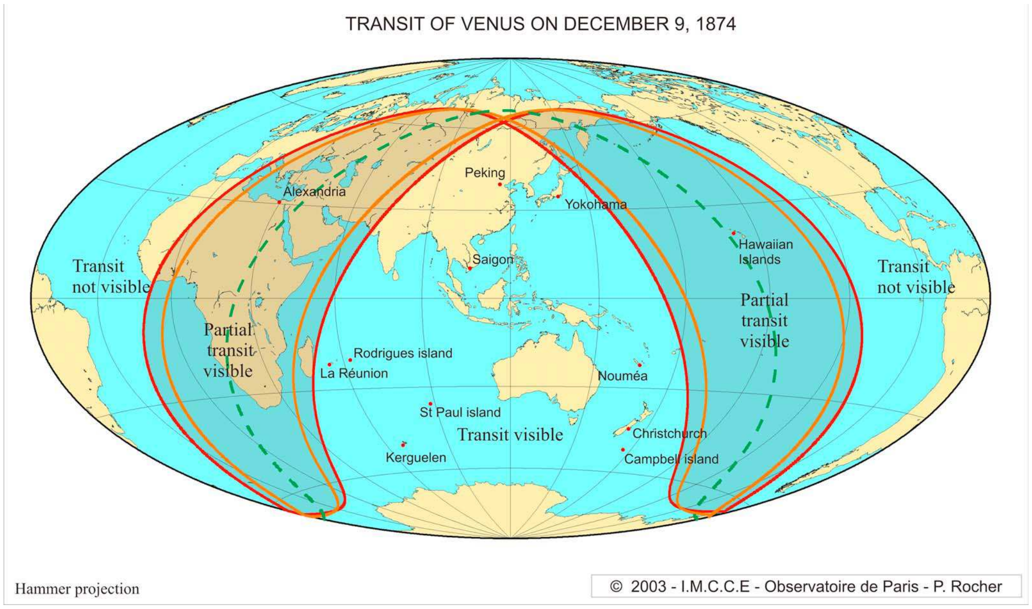


Figure 1. Map showing where the 9 December 1874 transit of Venus across the Sun was visible from the Earth. The red dots indicate the locations where the different nations sent their scientific expeditions to observe the transit. Saint Paul Island is located in the South Indian Ocean (Credits: IMCCE, Observatoire de Paris, P. Rocher).

the Southern Hemisphere [*Hunter et al.*, 2003; *Woodworth et al.*, 2005, 2010; *Testut et al.*, 2006; *Watson et al.*, 2010]. In section 2, we will review the history of sea level observations at Saint Paul Island from the nineteenth century to the present. Section 3 will be devoted to the calculation of the MSL values and their uncertainty from the raw data. The estimation of the long-term sea level trend and the discussion of the results will be presented in section 4. Finally, section 5 contains the conclusions of the study.

2. Sea Level Observations at Saint Paul Island

2.1. Historic Measurements

[6] In the early 1870s, the astronomers of many nations gathered to prepare observation task forces for an important astronomic phenomenon, the transit of Venus across the Sun, due to take place on 9 December 1874, in the middle of the Austral summer. This phenomenon was of major importance as it would permit an accurate determination of the Astronomical Unit, that is, the distance between the Sun and the Earth, which is used to estimate the distances between the planets in the solar system.

[7] The islands that make up the actual TAAF represent the majority of the land in the Indian Ocean between 45° and 50° south and they were of particular interest for the observations of the Transit. The French Academy of Sciences organized expeditions to China, Japan, New Caledonia, New Zealand (Campbell Island) and Saint Paul Island (Figure 1). The Saint Paul Island expedition was led by Ernest Mouchez who set up instruments on the island in September 1874. The expedition stayed at Saint Paul Island until the beginning of 1875. During that period, a tide staff was installed and sea level readings were continuously recorded every half an hour from 6 October 1874 to 31 December 1874. The mean value of these measurements (uncorrected for the inverse barometer effect) was calculated on-site and then transferred to a mark struck in a nearby rock (Figure 2), providing a valuable reference point with which to estimate the evolution of MSL at the island. Other variables such as atmospheric pressure, humidity and air temperature were also recorded. A summary of those observations was published by the French Academy of Sciences [*Mouchez*, 1878] together with a thorough description of the meteorological conditions [*Rochefort*, 1878]. The mark was rediscovered in 1994 during an archeological inventory, but it was attributed to the mean sea level data mentioned by

Figure 2. Photograph of the engraved mark of 1874 at Saint Paul Island with the inscription "Niv. moy" ("Mean level"). The horizontal line is 1.9 cm wide in width at the intersection with the vertical line (photograph taken in 2009).

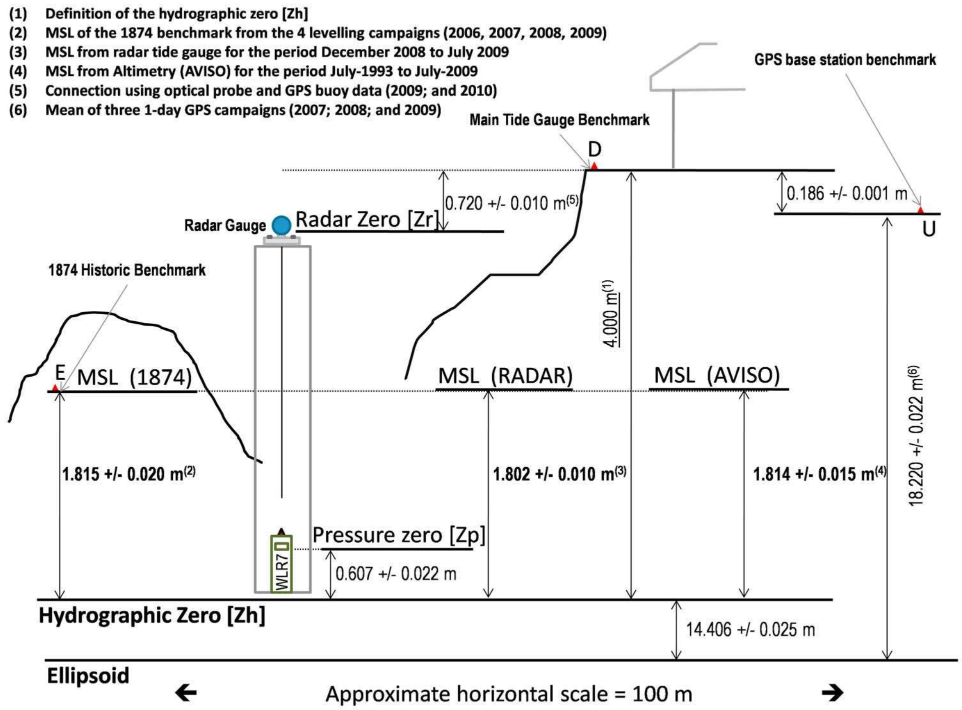


Figure 3. Schematic view of the Saint Paul Island installation and main results of the leveling with respect to the hydrographic zero "Zh." The uncertainties mentioned in this figure are the leveling errors (σ_L) indicated in Table 1. D, U, E denoted the location of the local benchmark network. Zr and Zp are the position of the instrumental reference of the radar and pressure gauge, respectively.

Mouchez [1878] only in late 2006 after an historical investigation (completed by the authors). The mark was subsequently leveled during the maintenance visits undertaken in 2006, 2007, 2008 and 2009 (the mission reports are available online at http://www.legos.obs-mip.fr/en/observations/rosame/communication/rapports/).

[8] From the *Mouchez* [1878] report, we digitized the high and low water heights that were corrected by him for the inverse barometric effect, as well as the daily mean barometric pressure reduced at MSL spanning the same whole period (6 October 1874 to 31 December 1874). The original raw half-hourly sea level and barometric pressure values from the expedition have not been traced as yet. However, a copy of tabulated hourly values (for October and November) was found at the SHOM archive (Service Hydrographique et Océanographique de la Marine) and used by *Gougenheim* [1949] to compute the tidal constituents at Saint Paul Island. All the above mentioned measurements and related historical documents have been used to assess the quality of the sea level observations, and to estimate the uncertainty associated with the 1874 MSL determination.

2.2. Modern Measurements

[9] The Saint Paul Island station is part of the ROSAME (Réseau Sub-antarctique et Antarctique du niveau de la MEr) tide gauge network (http://www.legos.obs-mip.fr/observations/rosame/), one of the French contributions to the Global Sea Level Observing System (GLOSS) program of the Intergovernmental Oceanographic Commission (IOC) of UNESCO [*Woodworth*, 1997]. The first modern tide gauge station at Saint Paul Island was established in 1994, and equipped with a subsurface pressure tide gauge installed in a stilling well. Measurements began on 25 October 1994 and continued to the present with only a few short gaps due to reasons such as battery failure or satellite transmission problems. Most of the available sea level data were acquired with Aanderaa WLR7 subsurface pressure tide gauges. Those gauges measure changes in the total bottom pressure (including sea level and atmosphere) and are equipped with a temperature sensor and occasionally a conductivity sensor. There is also an atmospheric pressure sensor installed in a nearby hut. The sea level measurement is derived from the difference between bottom and atmospheric pressure taking into account the value of local gravity and the density. Density is derived from in situ ocean temperature and salinity when available. But for most part of the record the salinity was assumed to be constant. The assumption leads to submillimeter uncertainty in the sea level calculation. From November 2008 onward, the station was also equipped with a radar tide gauge (Khrone Optiflex) installed in the same stilling well as the pressure tide gauge. Unfortunately, only 7 months of data have been recovered because of an electronic failure of the station, resulting in a loss of data since July 2009. Due to its remote location, maintenance visits at Saint Paul Island are generally undertaken only once a year during the logistical rotation of the French research vessel Marion Dufresne. This imposes serious handicaps on the ability to react to a problem, once detected, irrespective of the measurement system. In addition to this, being part of a national protected area, access to the island is strictly limited and those visits must be extremely short, typically a few hours.

Table 1. Summary of the MSL and Associated Errors for the Different Periods and Instruments[a]

Period	Instrument	MSL/Zh	σ_Q (cm)	σ_L (cm)	σ_S (cm)	σ_T (cm)
1874	Staff readings	181.5	2	2	5.1	5.8
2008–2009	Radar gauge	180.2	1	1	4.1	4.3
1994–2009	*Pressure gauge*		*2*	*2.2*		
1993–2009	*Altimetry*	*181.4*	*2*	*1.5*	*~0*	*2.5*

[a]Here σ_Q is the instrumental error, σ_L is the leveling error, and σ_S is the sampling error. Furthermore, σ_T is the total error (quadratic sums of the three previous ones) associated with each MSL estimate. The two last rows (in italics) are purely indicative and they were not used to compute the sea level trend.

[10] Over the period 1994–2005, maintenance visits basically consisted in replacing the batteries and sensors. From 2006 onward, other operations have been added. These have been related to the importance of controlling the tide gauge datum for monitoring of a possible vertical movement of the instrument. Consequently, regular leveling campaigns have been undertaken. Finally, in November 2008, a GPS equipped buoy was deployed during two days in the vicinity of the tide gauge station in order to calibrate and define the datum of the radar sensor. GPS equipped buoys have proven useful to achieve in situ calibrations of tide gauges located in remote islands [e.g., *Watson et al.*, 2008]. Further calibration was also performed in 2008 and 2009 by means of visual observations using an optical probe, confirming the results obtained with the GPS buoy and showing the stability of the radar sensor zero reference. A summary of the leveling and MSL values is shown in Figure 3. The MSL for the recent period used in this paper was derived from the radar measurements over the 7 months period from December 2008 to July 2009 (Table 1).

3. Uncertainty Estimates

[11] As already mentioned, an important focus of this paper is to carefully evaluate the sources of uncertainty affecting the estimation of the MSL at both extremes of our timeline. This estimate is affected by three categories of errors. A first one, σ_Q, can be related to the intrinsic quality of the data used to produce the MSL estimate. The second one is related to the connection of the MSL to a common datum (Zh) during the measuring period (defined as the leveling error, σ_L). Finally, it is essential to consider to what extent the estimated averages over a short period are representative of the value over an extended period (one or two decades), as the short-period measurements can be affected by seasonal and interannual variability (defined as the sampling error, σ_S).

[12] In sections 3.1 and 3.2 we will assess all those errors both for the historical and the modern measurements. In some cases the errors will be corrected for or considered negligible. In others, they will simply contribute to the overall uncertainty estimation. The results of this assessment are summarized in Table 1.

3.1. Historical Measurements

[13] The process that led to the MSL value in 1874 has been described in section 2. These observations are subject to a certain degree of inaccuracy, especially when taking into account that they had to be taken at night as well as day time and were read on a tide staff, so they could be affected by waves and reduced visibility. This aspect is minimized due to the fact that the tide staff was installed inside the crater which plays the role of a natural stilling well. Some tests on the hourly data showed their good quality. Indeed the standard deviation of the residuals of the 1874 sea level (i.e., the detided signal) is equivalent to the same quantity computed over the same period in recent years using a modern tide gauge (about 7 cm) and the results of the harmonic analysis for the main tidal constituents are consistent with the ones obtained from the modern records. The tide staff was graduated in centimeters according to *Mouchez* [1878]. Based on our experience on tide staff reading and due to the particular sea conditions inside the crater, we established a σ_Q = 2 cm (Table 1).

[14] In late 1874, the MSL observed was transferred to a stable rock where a mark was struck. The leveling operations that had to be performed may have also included some error. Nevertheless, at the end of the nineteenth century, leveling instrumentation and techniques were developed enough as to assume that this error was well below 1 cm over short distances (a hundred meters). Moreover, the expedition team was composed of good sailors and astronomers used to leveling techniques and committed to obtain the most accurate observations. The shape of the mark however, may pose other difficulties. It is reasonable to think that the mean sea level ("Niv. Moy" in Figure 2) corresponds to the intersection between the horizontal and the vertical line. However, the "point" of intersection is in fact 1.9 cm in width. So we took 2 cm to be the error in the transfer of the 1874 MSL to the nearby rock. That value corresponds also to the uncertainty of transfer of the historical mark to Zh as reflected by the standard deviation of the four successive leveling operations carried out in recent years (maximum difference equal to 3.5 cm). Therefore, the adopted leveling error for the historical mark is the standard deviation of the four successive leveling σ_L = 2 cm (Table 1).

[15] Regarding the sampling error σ_S, the MSL calculated in 1874 was the result of 90 days of tide staff measurements taken every half an hour. Ideally, only continuous, several decades-long records should be used to estimate long-term sea level trends, but this is unfortunately very rare for the Southern Hemisphere. Typically, sea level trends are calculated using annual means, which should include at least 11 or 12 monthly means [*Woodworth and Player*, 2003]. The MSL resulting from a 3 month measurement period could be affected by seasonal variability and therefore not be representative of the annual mean. Likewise, interannual variability linked to various oceanographic and meteorological phenomena must also be taken into consideration. In order to tackle this problem and assess the sampling error, we developed a methodology based on the analysis of the monthly mean values of the altimetric time series over the modern period (1994–2009). The uncertainty related to undersampling also affects the MSL obtained in 2009. This is addressed in section 3.2.

[16] We can also ask to what extent the meteorological conditions, and in particular the atmospheric pressure con-

ditions, were anomalous in that 3 month period as this could affect the sea level determination, and subsequently the estimated rate of sea level change. In this regard, observational evidence showed that the mean value of atmospheric pressure presented in the report [*Rochefort*, 1878] does not differ significantly (<0.5 mbar) from the mean value obtained in Amsterdam Island for the same months over the period 1950–2009 for which meteorological data are available.

3.2. Modern Measurements

[17] Modern records are also affected by instrumental errors. Subsurface pressure tide gauges such as the WLR7 are subject to well known, yet difficult to correct, problems such as the sensor drift and offsets [*Watts and Kontoyiannis*, 1990; *Testut et al.*, 2006]. Another relevant source of error at the Saint Paul Island station was due to the atmospheric pressure sensor, used to correct the tide gauge measurements. After comparison with atmospheric data taken at the closest meteorological station of Amsterdam Island, a linear drift of 1 mbar yr^{-1} for the period 1994–2006 was detected. Sea level data were recalculated using atmospheric pressure measured at Amsterdam Island after verifying that the two detrended data sets were highly correlated. Therefore, this source of error was eliminated, keeping in mind that this procedure removes the drift in the barometer but not in the WLR pressure sensor. The only way to estimate and remove the bottom pressure sensor drift is by carrying out frequent tide staff calibrations.

[18] Another important source of uncertainty is related to the change of equipment. Whenever a tide gauge is installed or relocated, precise leveling with respect to a permanent benchmark must be undertaken in order to have a common reference for the sea level time series. Even if the replacement operations are done carefully, there is always a risk of the new gauge not resting exactly in the same position. In addition to that, transducers may be located in different positions within the body of the instrument. This position is generally indicated in the manufacturer's specifications, but offsets can also be found occasionally. The offset can be calculated through a calibration operation whereby the sea level data obtained with one sensor are compared with sea level data obtained with a reference instrument whose measurements are confidently connected to Zh. For this reason calibration and leveling operations are extremely important when aiming to achieve a reliable long-term sea level time series. Our experience has shown that laboratory calibration of instruments is not sufficient and cannot be used as a substitute to in situ calibration which is the only way to determine the real offset and drift affecting a given sensor.

[19] Unfortunately, as we have mentioned, these operations have only been possible from 2008 onward. This implies that mean sea levels obtained previously could be affected by those errors associated with changes in the gauge contact point. Those errors, together with the drift problem mentioned above raised some doubts concerning the suitability of WLR7 data to calculate a long-term sea level trend and prevented us from using those data directly in the calculation of the trend.

[20] Despite these limitations, measurements taken with the subsurface pressure sensor during the period 1994–2008 could still be valuable to provide upper bounds of the seasonal and interannual variability. In order to connect those measurements to Zh, we used the altimetric sea level anomalies (SLA) as a reference (gridded AVISO merged products from http://www.aviso.oceanobs.com/en/data/products/index.html). This is quite an unusual combination of tide gauge and altimetry, as the former is generally used to calibrate the latter. In a first step a time series of SLA was extracted from the gridded product at the location of Saint Paul Island. Then this time series was connected to Zh by a simple difference between the radar gauge sea level (corrected for inverse barometer, detided and smoothed with a 15 days running mean filter) and the SLA over the 7 month period in common from December 2008 to July 2009. The derived offset of the SLA time series has a mean value of 180.5 cm with respect to Zh. Although this method may appear quite crude at first, it led to a root mean square (RMS) difference of only 1.5 cm between the radar gauge and the SLA. This value was used as the conservative leveling error σ_L for the altimetric MSL (Table 1). This relatively low RMS difference between both signals is probably due to the particular location and small size of Saint Paul Island in the middle of the ocean, which makes it highly representative of the sea level seen by the altimeter. This was confirmed by the high value of the correlation of the monthly mean values (Figure 4).

[21] In a second step we used the whole referenced SLA to tie the seven periods where the subsurface pressure sensor was doubtfully referenced before 2008. With this method we linked the instrumental pressure sensor reference for the whole period (1994–2008) to Zh at a level (few cm) sufficient to use the tide gauge series for the estimation of the seasonal and interannual variability. Figure 4 shows the monthly mean values over the tide gauge period (1994–2009) for both the tide gauge and the altimetric sea level. For this period the correlation is 0.94 and the RMS of the difference is 2.2 cm. The average seasonal cycle is depicted in Figure 5 (top) for the altimetric sea level data (the results were equivalent for the tide gauge data, due to the high similarity between both signals). The average seasonal cycle showed a peak to peak variation of about 8 cm. This cycle is in phase with the sea surface temperature cycle observed at the station (amplitude 2.4°C) with a maximum at the end of the Austral summer (February) and minimum at the end of Austral winter (August/September). The striking feature is that this average cycle is largely hidden by the high variability observed from one year to another (Figure 5, bottom). The interannual variability of the sea level given by the plot of the annual mean in Figure 4 is significantly less important showing a standard deviation of 2.7 cm. We estimated the MSL uncertainty due to seasonal and interannual variability as the standard deviation of the altimetric time series averaged over N months (N = 3 for the historic measurements and N = 7 for the 2009 radar measurements). With this method the sampling error yielded σ_S = 5.1 cm for the historical MSL and σ_S = 4.1 cm for modern radar MSL (Table 1). The sampling error for the altimetric MSL over the whole period 1992–2009 was considered to be negligible and chosen to be zero, meaning that a 17 years mean was considered highly representative of the true recent MSL at this location. Tests based on different values of the amplitude for the nodal tide cycle (18.6 yr) showed that the

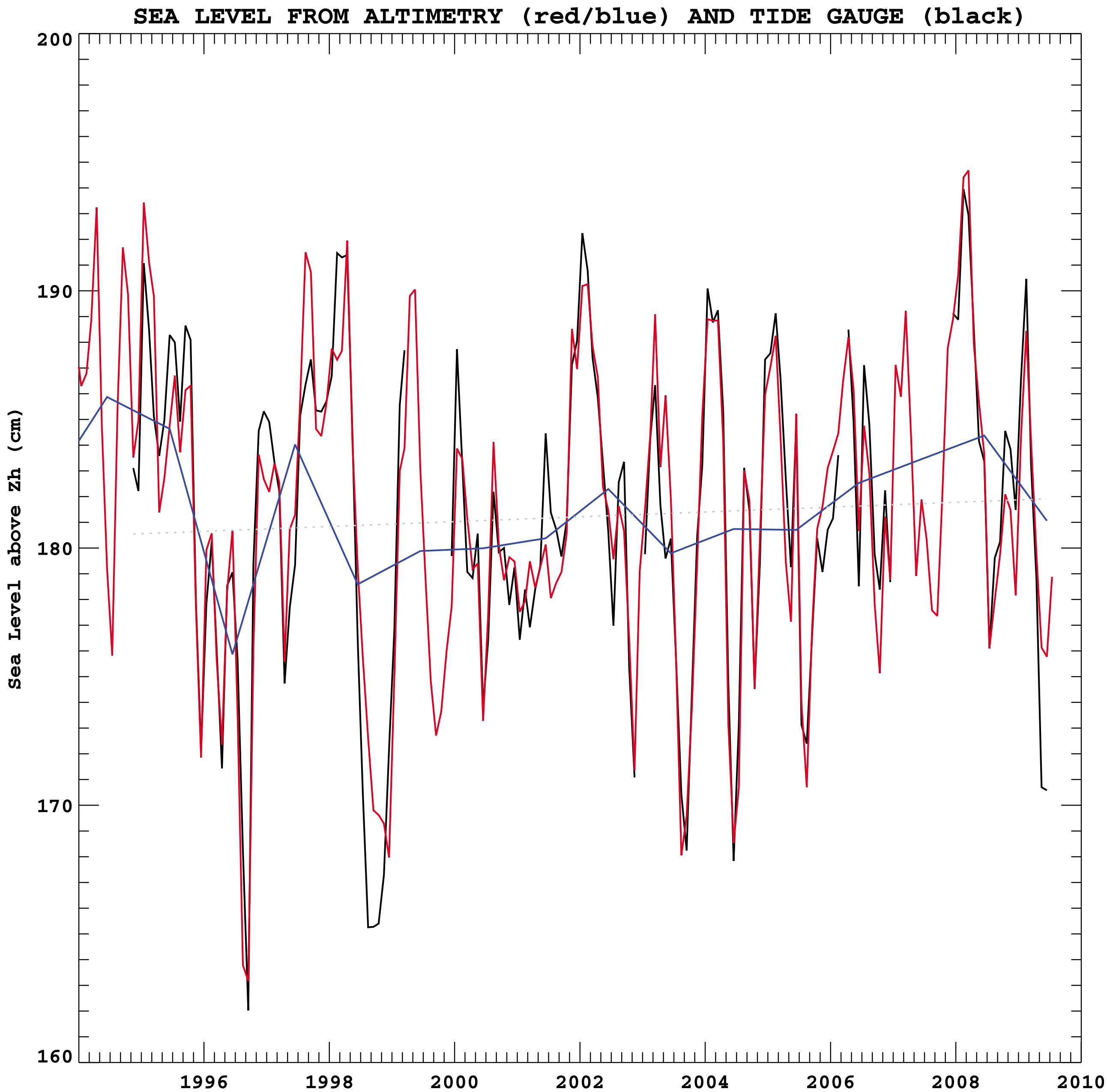
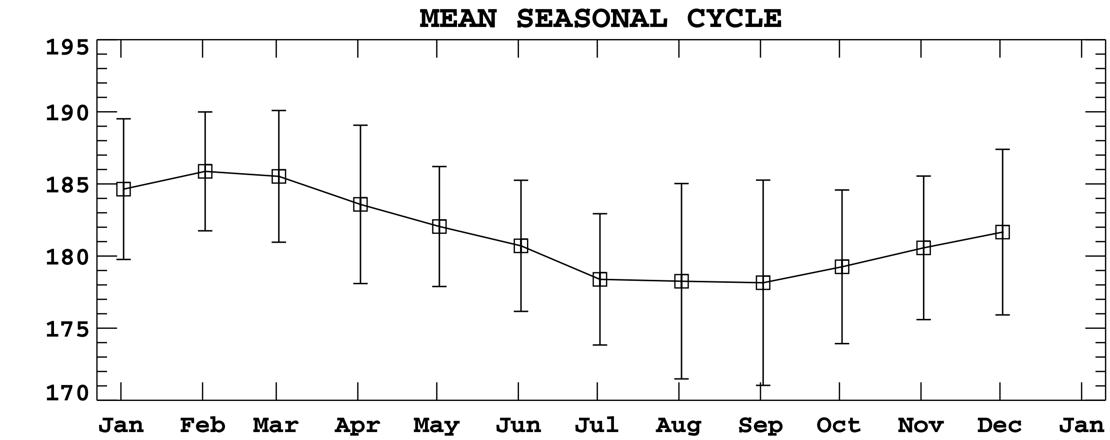


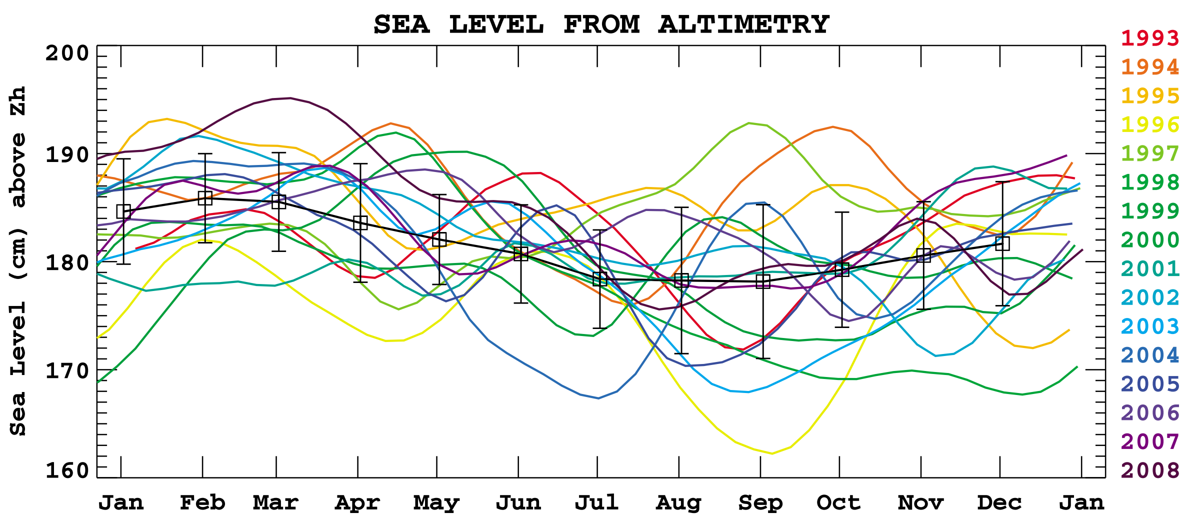
Figure 4. Monthly mean sea level series obtained with the WLR7 subsurface pressure gauges (in black) and the altimetric SLA (in red) for the period (1994–2009). The RMS variability of the monthly means is around 6 cm for both series, the correlation coefficient is 0.94 and the RMS difference is 2.2 cm. The blue curve is the annual mean of the SLA, its RMS variability is 2.7 cm for the 1992–2009 period.

induced error in MSL trend (<0.1 mm yr^{-1}) at Saint Paul Island due to this term would be negligible in comparison with the above sampling error and therefore was not included in σ_S.

[22] In regards to the radar tide gauge, previous experiences with radar sensors [*IOC*, 2006; *Miguez et al.*, 2008a, 2008b] showed promising results for this type of technology in terms of accuracy and long-term stability. Nevertheless, a close inspection of the radar measurements at Saint Paul Island, and their comparison with the bottom pressure data, allowed the detection of spurious values that are due to an anomalously short warm-up time of the radar sensor. Indeed when the radar is not sufficiently warmed up, a default value (i.e., the full size of the radar rod) is allocated to the first few raw 1Hz samples, affecting in return the sea level observation based on the mean value of 40 samples. It seems clear that no technology is free from faults and that having two instruments operating simultaneously is worthwhile. After correcting the spurious data we assigned a σ_Q = 1 cm for the radar measurements (Table 1), which is probably an overestimate of the true instrumental error. Unlike the subsurface pressure tide gauge, the radar gauge was carefully leveled



SEASONAL CYCLE PEAK TO PEAK = 7.7 / MIN= 178.2 in Sep / MAX= 185.9 in Feb



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Mean	184.6	185.9	185.5	183.6	182.0	180.7	178.4	178.3	178.2	179.3	180.6	181.7=	181.5
RMS	4.9	4.1	4.6	5.5	4.2	4.5	4.6	6.8	7.1	5.3	5.0	5.7=	5.9

Figure 5. (top) Mean seasonal cycle of sea level computed using the average of the 18 years of monthly means from altimetry over the period 1992–2009. The error bars are the standard deviation for each month as shown by the scale at the bottom. (bottom) Monthly means from altimetry for each year over the same period. The 181.5 and 5.9 are the averages and RMS of the monthly values.

and calibrated in December 2008 after its installation. Two reference instruments were used, the GPS buoy and an optical probe (manual measurements), providing, respectively, 70 and 15 instantaneous measurements that we subtracted from the ones taken with the radar at the same time. This permitted not only the connection of the radar measurements to Zh, but also to derive absolute (geocentric) sea level heights in the ITRF2005 reference frame [*Altamimi et al.*, 2007]. The most recent calibration operation undertaken in 2009 yielded the same results within a cm, confirming that the radar sensor experienced no significant drift. The results of all those leveling and calibration operations are summarized in Figure 3.

4. Results and Discussion

[23] Once the MSL were calculated at both extremes of the timeline and their respective errors estimated, the MSL over the past 135 years was derived by simply calculating the difference and assuming that the change was linear. As shown in Figure 6, we obtained a sea level trend relative to the land of −0.1 ± 0.3 mm yr^{-1}. The uncertainty associated

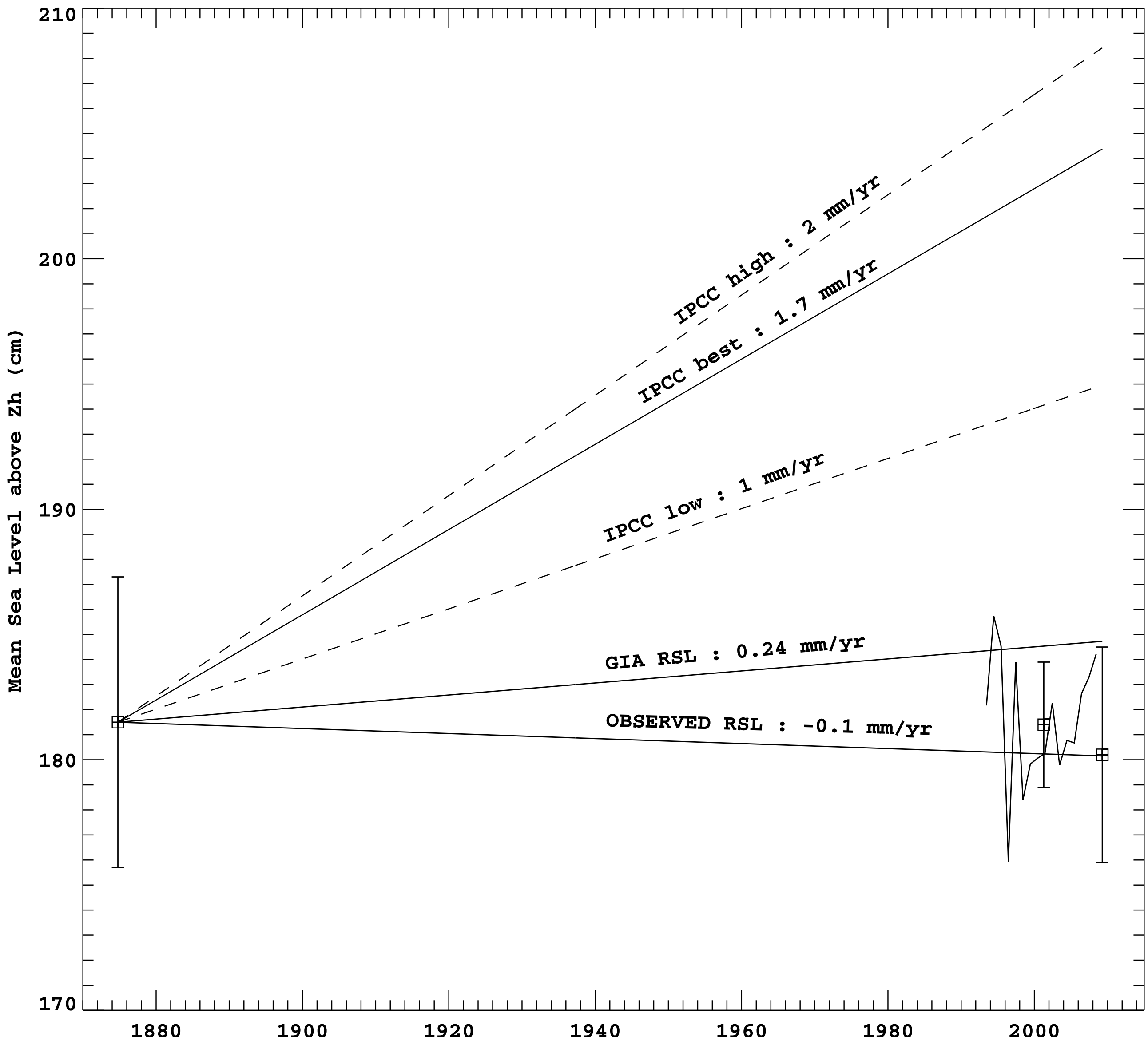


Figure 6. MSL estimates at Saint Paul Island relative to the hydrographic zero for the historic observations (1874) and the recent observations (2009). The error bars indicate the uncertainty of the estimates ($\pm\sigma_T$, defined in Table 1). The curve shows altimetric annual mean sea level at Saint Paul Island derived from the AVISO product and constrained by the overlap with the radar data. The associated overall MSL is shown by the square boxes for the different period. We have also plotted the line of the GIA-induced relative sea level change rate, and the lines to indicate the lower, upper, and best global sea level trend estimate over the 20th century [*Bindoff et al.*, 2007].

to the trend was derived from the formula $\sigma^2_{trend} = (\sigma^2_{1874} + \sigma^2_{2009})/(2009 - 1874)^2$ where σ_{1874} and σ_{2009} are the overall uncertainties of the 1874 and 2009 MSL values, respectively, given in Table 1. In other words, there is no observational evidence of significant relative sea level change at Saint Paul Island.

[24] We considered two sources of potential vertical land motion. First, radial displacement of the land at Saint Paul Island due to glacial isostatic adjustment (GIA) is predicted to be −1.6 mm yr^{-1} (subsidence) over the past hundred years using the ICE-5G VM2 model from *Peltier* [2004]. The GIA-induced relative sea level using that model is estimated to be +0.24 mm yr^{-1} over the past hundred years including both radial displacement and geoid readjustment processes. Both GIA-predicted and observed relative sea level rates are consistent, implying no evidence of sea level rise from other climate contributions at Saint Paul Island [*Bindoff et al.*, 2007]. The second potential source of land motion is volcanism, which is more difficult to evaluate at Saint Paul Island. The only recorded historical eruption took place in 1793 from a vent on the lower southwestern flank (http://www.volcano.si.edu/world/volcano.cfm?vnum=0304-002). Some geothermal activity remains located along the caldera rim and the caldera bay. The possibility of vertical movements of this dormant volcano cannot be discarded associated with magma intrusions (land uplift) or posteruptive

land subsidence taking place at rates comparable to the ones found in our study. The local seismic activity at Saint Paul Island is weak, at least for the available period of measurements. The nearest ridge earthquake (Mw5.1, 2003/12/31 08:32:15) was detected at a distance of 40 km from the island. In the last 30 years, only 12 ridge events in the vicinity of Saint Paul Island have been large enough (Mw4.9 to 6.4) to be detected by the global network (http://www.globalcmt.org/), and these predominantly occurred on the transform segments of the ridge (A. Maggi, personal communication, 2010). From geological considerations and geophysical data no assessment of vertical land motion could be inferred.

[25] Yet space geodesy may provide a solution to determine the rate of land motion affecting the tide gauge site, especially the Global Positioning System (GPS) using continuously operating stations [e.g., *Wöppelmann et al.*, 2007]. For the time being, the three 1-day GPS campaigns carried out at Saint Paul Island in 2007, 2008, and 2009, could not provide a reliable estimate of land motion, because of the large error bars of the 1 day GPS height estimates and short span of measurements. Figure 3 shows the average ellipsoidal height and RMS of the GPS sessions computed using the Precise Point Positioning (PPP) technique from the Canadian SCRS-PPP online service (http://www.geod.nrcan.gc.ca/products-produits/ppp_f.php). Another possible space geodetic source of information could be derived from the Doppler Orbitography Radiopositionning Integrated by Satellite (DORIS) system. The DORIS beacon at Amsterdam Island indicates a vertical land uplift of 1.76 ± 0.4 mm yr^{-1} over the period 1993–2009 [*Altamimi and Collilieux*, 2010]. However, the vertical velocity estimate is based on four discontinuous DORIS position time series (discontinuities due to beacon malfunctions and changes). In addition to this, Amsterdam Island is located approximately 100 km north of Saint Paul Island, and the two islands are separated by a submarine fault. In spite of all these reservations, applying the DORIS-observed land uplift rate at Amsterdam to Saint Paul Island leads to a rate of absolute (geocentric) sea level change at Saint Paul Island in agreement with the generally accepted global average change over the past century [*Bindoff et al.*, 2007].

5. Conclusions

[26] From geological considerations and available geophysical and geodetic data, we cannot definitely conclude on the issue of land motion affecting the Saint Paul Island sea level record. However, we have confidence in the rate of relative sea level change observed over the past 135 years. Our result represents a carefully derived additional observational constraint to take into account in future investigations of spatial variations of sea level change. All the observations were connected to the same datum by means of historical investigation, precise leveling operations, and an original calibration procedure for the tide gauge data using satellite altimetry and a GPS buoy. Particular attention was paid to rigorously assess the uncertainties and obtain a realistic error budget for the historical and present mean sea level estimates. Saint Paul Island has become a reliable sea level observing station whose time series origin has been extended 135 years, back to 1874. It now consists of high-quality instruments which hopefully will soon be complemented by a permanent GPS station to solve the land motion issue in the near future.

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